E298A/EECS290B: Problem Set 1 Solutions

1. ***Plot the theoretical maximum resolution as a function of gap size for an optical contact printer for λ = 248 nm, 365 nm and 436 nm. Also, plot the theoretical maximum resolution as a function of gap size for an x-ray proximity printer at λ = 0.1, 1 nm and 10 nm. In each case, what gap size corresponds to a Fresnel number of 1?***

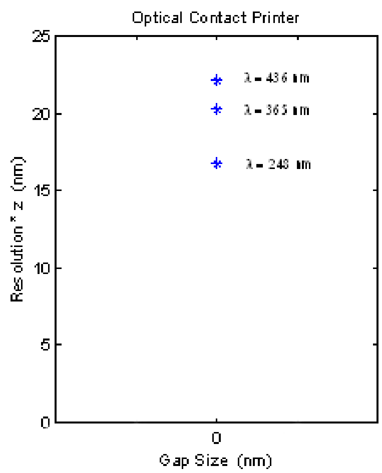
For shadow printing techniques, the theoretical resolution R (defined by the minimum resolved dimension using a grating mask – half a grating period) is given by:

$$R = \frac{3}{2}\sqrt{\lambda\left(s + \frac{z}{2}\right)}$$

where λ = wave length of incident radiation
s = size of gap between the mask and photoresist
z = resist thickness

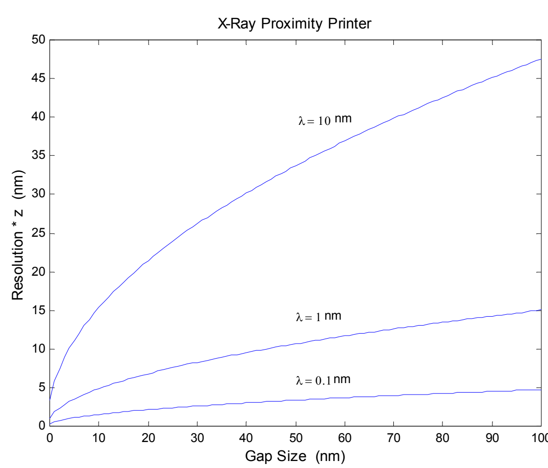
For an optical contact printer, s = 0, and the resolution is given by:

$$R = \frac{3}{2}\sqrt{\frac{\lambda z}{2}}$$



R(λ = 258 nm) = 16.7
R(λ = 365 nm) = 20.3
R(λ = 436 nm) = 22.1

For an x-ray proximity printer, s > 0, and the resolution, and the resolution can be plotted as a function of gap size.



By thinking about the Fresnel numbers for the various cases, we can see that at very short wavelengths we are essentially casting shadows. Resolution in these cases is limited by the source divergence and by factors such as photoelectron emission in the resist. Note that although hard x-rays should provide sharper images, it becomes very difficult to make a mask with suitable contrast. At longer wavelengths we can still, in principle, maintain a large Fresnel number by using very thin resist, though the tendency of the light to spread out from an aperture is very strong. For practical resist thicknesses the UV wavelengths all give about the same 0.25 μm resolution. Additionally, the transmission of light through sub-wavelength apertures drops off dramatically. These are the same problems encountered in near-field optical microscopy (NSOM).

The Fresnel number = 1 when:

$$1 = \frac{r^2}{\lambda(s + \frac{z}{2})}$$

where r = feature size

Solving for s:

$$s = \frac{2r^2 - z\lambda}{2\lambda}$$

For the optical contact printer, s = 0 by definition, so it is not possible to achieve a Fresnel number of 1.

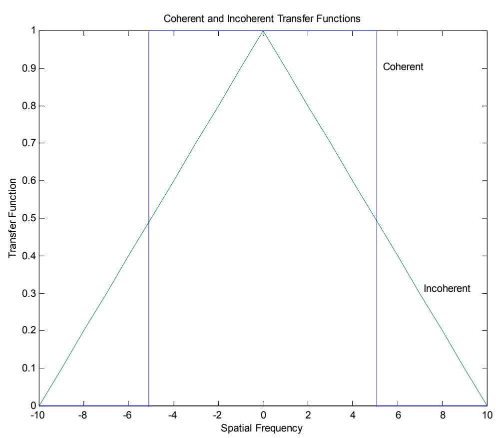
For the x-ray proximity printer,

$$z(nm) = 5(2r^2 - \frac{1}{10}z) \quad \text{for l = 0.1 nm}$$

$$z(nm) = \frac{1}{2}(2r^2 - z) \quad \text{for l = 1 nm}$$

$$z(nm) = \frac{1}{20}(2r^2 - 10z) \quad \text{for l = 10 nm}$$

2. ***Sketch the coherent optical contrast function and the incoherent optical transfer function. Explain why a point spread function approach can be used in image modeling for incoherent systems but not for partially or fully coherent systems. Can it be used for e-beam systems?***



A coherent imaging system means that the object and image have a linear relationship in electric field. If U_g and U_i are the electric field in the object and image planes respectively, the fields are related by:

$$U_i = U_g \otimes h$$

where h is the impulse response of the optical system, which is equal to the fourier transform of the aperture of the imaging lens. $\otimes$ represents convolution. The image intensity is then the amplitude square of the electric field in the image plane, $I_i = \left| U_g \otimes h \right|^2$.

On the other hand, an image of an incoherent system varies linearly with the object in intensity, i.e.,

$$I_i = I_g \otimes |h|^2 = |U_g|^2 \otimes |h|^2$$

Assume the aperture function of the lenses be circular. The impulse response h of an optical system is a sinc function, which is similar to sinc function except the sine function is replaced by a Bessel function of the first kind. The system transfer function H is a Fourier transform of the impulse response.

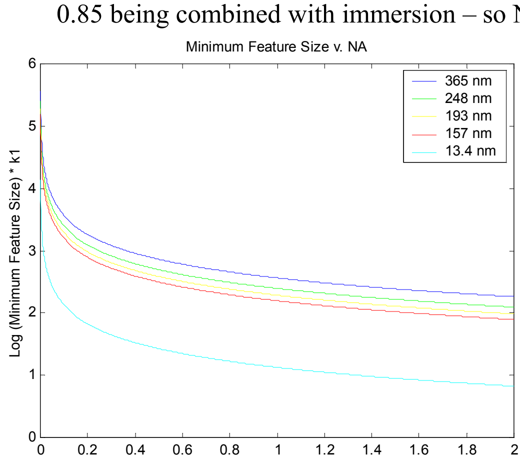
For a coherent imaging system, the transfer function after Fourier transform has the shape of the aperture, circular top hat with unity inside the circle. But lateral dimension of the top hat changes with observation distance from the lens and the wavelength.

Because the image and object are linear in intensity in an incoherent system, the impulse response is $|h|^2$ and the transfer function will be the Fourier transform of $|h|^2$. This transfer function is called optical transfer function (OTF). It can be shown that in the frequency domain, OTF is equal to the autocorrelation of H, the Fourier transform of h.

In incoherent systems we essentially are not concerned with phase, i.e. interference, effects, so the image is obtained simply by convolving the object with a PSF. In direct write e-beam, we are writing with a small, Gaussian, probe – a very simple PSF. There are no interference effects, so a PSF approach is appropriate. In projection e-beam, the imaging is also incoherent, given the nature of the source and the pupil-fill. In electron microscopy, which frequently has relatively coherent illumination, a PSF approach does not work.

3. ***Plot the minimum resolvable feature size for an optical system using λ = 13.4 nm, 157 nm, 193 nm, 248 nm and 365 nm light as a function of numerical aperture. In the case of 193 nm lithography, immersion lenses have been proposed. What difference will this make to the minimum resolvable feature size?***

Note that the industry is now proposing "hyper-NA" systems – think of a dry lens with an NA of 0.85 being combined with immersion – so NAs above one are important.



The minimum resolvable feature size for an optical system can be described as:

$$R = k_1 \frac{\lambda}{NA}$$

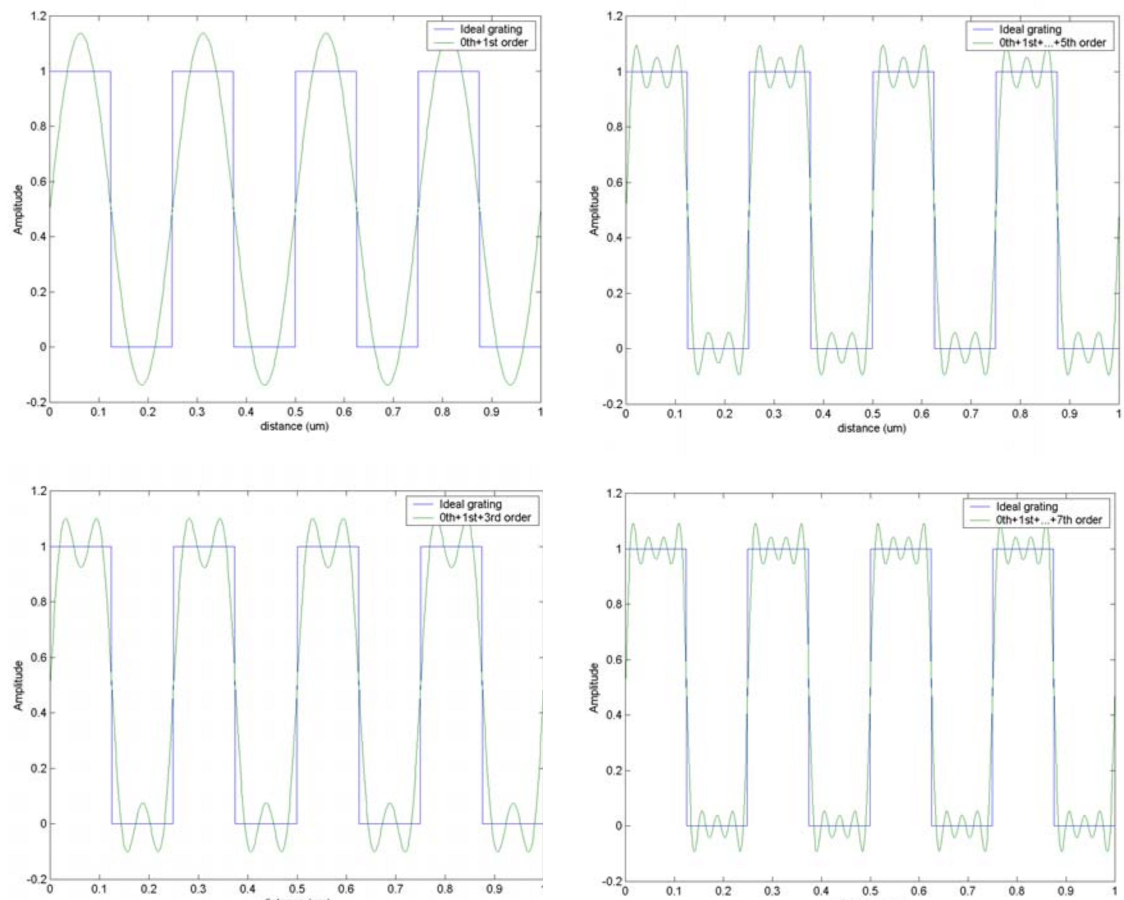
Immersion allows the NA to be greater than 1. If we compare resolutions at the larger NA (>1) and longer wavelengths with the resolutions at small NA (< 0.1, which is typical for optics used at this wavelength) at the 13.4 nm wavelength, we can see that the resolutions are comparable.

4. ***Consider a grating of period p that produces a square wave intensity output m(x) at its surface. Expand m(x) into its harmonic components and plot m(x) for the 1^{st}, $1^{st}+2^{nd}$, $1+2^{nd}+3^{rd}$, $1+2^{nd}+3^{rd}+4^{th}$ terms. Plot the image you would expect for p = 0.5 um, λ = 193 nm and NA = 0.7 assuming coherent illumination.***

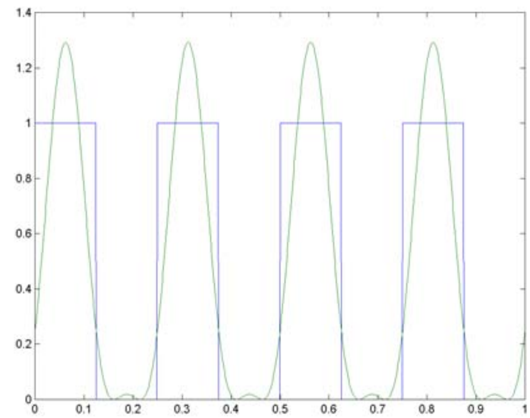
Let m(x) describe a square wave with a step rising at the origin. Using Fourier series expansion, m(x) can be expressed as a series of sinusoidal functions:

$$m(x) = a_0 + \sum_{n=1}^{\infty} a_{2n-1} \sin(2\pi(2n-1)\frac{x}{p}) \qquad \text{where } a_0 = \frac{1}{2},\ a_{2n-1} = \frac{2}{(2n-1)\pi}$$

Because the lines and spaces have equal width, only odd orders are needed in the expression.



Since a square grating diffracts light according to $p\sin\vartheta_n = n\lambda$, where ϑ_n is the diffraction angle in the nth diffraction order, ϑ_n must be less than the numerical aperture in order for the lens to capture the diffracted light. For p = 0.5 μm, λ= 193 nm, and NA= 0.7, only the zeroth and first order lights can pass through the lens. The electric field amplitude is plotted in the top graph above. Since the system is coherent, the image intensity is amplitude square of the electric field. Thus the image should look like:



5. ***Write down an expression for the image intensity in a coherent system in terms of Fourier transforms of the mask and the lens filter function, treating the lens as a low pass filter.***

The arguments have been stated in the solution of problem 2. The expression is:

$$I_i = \left| U_g \otimes h \right|^2$$

where U_g is the electric field in the object plane, h is the impulse response of the system and is equal to the fourier transform of the aperture/mask.

6. ***Explain why different types of illumination, e.g. annular, dipole, quadrupole, are employed in semiconductor lithography.***

The basic idea is to enhance the contrast/resolution of the features we are interested in. Since the set of features in lithography is far from random, in contrast to microscopy, we can effectively consider the object (mask) in Fourier space and work out how to deliver illumination to those components we are interested in printing, whilst minimzing the amount of light going elsewhere. The simplest case is for lines oriented in a single direction. Considering a grating again, we can see that rather than needing to image it with the +1, 0 and -1 orders, it is enough to use just the +1 and 0. This suggests that by tilting the illumination off axis we can arrange just that situation. For reasons of symmetry, we use two illumination spots (dipole) for features running in x or four (quadrapole) for features running in x and y.

7. ***Maskless lithography has been proposed many times as a cheap alternative to conventional IC lithography. Investigate the current contenders – do you think they will succeed? Why or why not?***

There are many maskless lithography candidates: scanning probes (contact, near-field), e-beam and optical direct-write, e-beam and optical multi-beam systems, and projection systems, both e-beam and optical, that effectively employ a dynamically addressable mask. The primary issue that affects all of these is low throughput, due typically to data handling requirements or available source power. At face value this is not a fatal flaw – you can just buy more (possibly cheaper) tools to overcome this and you will still come out ahead on mask cost. However, it appears, that for the throughputs currently predicted, that the cost of owning all these additional tools still outweighs the elimination of the mask cost.